

**BEHAVIOR OF FRP  
COMPOSITE-STRENGTHENED  
BEAMS UNDER STATIC AND  
CYCLIC LOADING**

**Summary Report**

**SPR 387.011**

# **BEHAVIOR OF FRP COMPOSITE-STRENGTHENED BEAMS UNDER STATIC AND CYCLIC LOADING**

## **Summary Report**

**SPR 387.011**

by

Damian Kachlakev, Ph.D., Assistant Professor,  
California Polytechnic State University,  
Civil and Environmental Engineering

and

Solomon Yim, PhD, PE  
Thomas Miller, PhD, PE  
Dharadon Seamanontaprinnya  
Oregon State University,  
Civil, Construction & Environmental Engineering

for

Oregon Department of Transportation  
Research Group  
200 Hawthorne SE, Suite B-240  
Salem OR 97301-5192

and

Federal Highway Administration  
Washington, D.C.

**June 2001**

Technical Report Documentation Page

1. Report No.  FHWA-OR-RD-01-20		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle  Behavior of FRP Composite-Strengthened Beams Under Static and Cyclic Loading - Summary Report				5. Report Date  June 2001	
				6. Performing Organization Code	
7. Author(s)  Damian Kachlakev, PhD, Civil and Environmental Engineering Department, California Polytechnic State University, San Luis Obispo, CA 93407 and Thomas Miller, PhD, PE; Solomon Yim, PhD, PE; Dharadon Seamanontapriya, Civil, Construction and Environmental Engineering Department, Oregon State University, Corvallis, OR 97331				8. Performing Organization Report No.	
9. Performing Organization Name and Address  Oregon Department of Transportation Research Group 200 Hawthorne Ave. SE, Suite B-240 Salem, OR 97301-5192				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No.  SPR 387.011	
12. Sponsoring Agency Name and Address  Oregon Department of Transportation Research Group and Federal Highway Administration 200 Hawthorne Ave. SE, Suite B-240 400 Seventh Street SW Salem, OR 97301-5192 Washington, DC 20590				13. Type of Report and Period Covered  Summary Report	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract  Small, concrete beams with no steel reinforcement were externally strengthened with eight different configurations of fiber reinforced polymer composites. The reinforcement configurations consisted of high and low modulus epoxy, high and low modulus fiber, and 1 and 2 composite layers. Load capacity tests were conducted for all eight configurations, and fatigue tests were conducted for two of the configurations. Beams with the higher modulus epoxy had more load capacity than beams with the lower modulus epoxy. However, this enhancement decreased as the failure mode changed from flexural failure to less desirable failure modes. The modulus of the resin had no effect on beam stiffness. The fatigue strength of the beams was strongly dependent on the load capacity of the beams; consequently, higher modulus epoxy could improve the fatigue performance of concrete beams.					
17. Key Words  fiber reinforced, composite, FRP, concrete, beam, epoxy, resin, modulus, load, capacity, fatigue, cyclic, static			18. Distribution Statement  Available from NTIS and Oregon Department of Transportation		
19. Security Classification (of this report)  Unclassified	20. Security Classification (of this page)  Unclassified	21. No. of Pages  11		22. Price	

# SI\* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	When You Know	Multiply By	To Find	Symbol
<u>LENGTH</u>				<u>LENGTH</u>				
in	inches	25.4	millimeters	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	kilometers	0.621	miles	mi
<u>AREA</u>				<u>AREA</u>				
in <sup>2</sup>	square inches	645.2	millimeters squared	mm <sup>2</sup>	millimeters squared	0.0016	square inches	in <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	meters squared	m <sup>2</sup>	meters squared	10.764	square feet	ft <sup>2</sup>
yd <sup>2</sup>	square yards	0.836	meters squared	m <sup>2</sup>	hectares	2.47	acres	ac
ac	acres	0.405	hectares	ha	kilometers squared	0.386	square miles	mi <sup>2</sup>
mi <sup>2</sup>	square miles	2.59	kilometers squared	km <sup>2</sup>	<u>VOLUME</u>			
<u>VOLUME</u>				<u>VOLUME</u>				
fl oz	fluid ounces	29.57	milliliters	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	liters	0.264	gallons	gal
ft <sup>3</sup>	cubic feet	0.028	meters cubed	m <sup>3</sup>	meters cubed	35.315	cubic feet	ft <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	meters cubed	m <sup>3</sup>	meters cubed	1.308	cubic yards	yd <sup>3</sup>
NOTE: Volumes greater than 1000 L shall be shown in m <sup>3</sup> .				<u>MASS</u>				
oz	ounces	28.35	grams	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	megagrams	1.102	short tons (2000 lb)	T
<u>TEMPERATURE (exact)</u>				<u>TEMPERATURE (exact)</u>				
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C	Celsius temperature	1.8C + 32	Fahrenheit	°F

°F

-40

0

32

40

80

120

160

200

212

°C

-40

-20

0

20

40

60

80

100

°F

-40

-20

0

20

40

60

80

100

°C

-40

-20

0

20

40

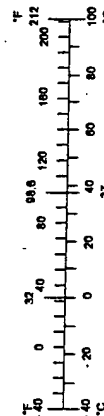
60

80

100

\* SI is the symbol for the International System of Measurement

(4-7-94 jbp)



NOTE: Volumes greater than 1000 L shall be shown in m<sup>3</sup>.

\* SI is the symbol for the International System of Measurement

## **ACKNOWLEDGEMENTS**

The authors would like to thank Mr. Steven Soltesz, Project Manager, Mr. Alan Kirk, Research Analyst, and Dr. Bernie Jones, Research Manager, of the ODOT Research Group for their suggestions and contributions to this project.

## **DISCLAIMER**

This document is disseminated under the sponsorship of the Oregon Department of Transportation and the U.S. Department of Transportation in the interest of information exchange. The State of Oregon and the U.S. Government assumes no liability of its contents or use thereof.

The contents of this report reflect the views of the author(s) who are solely responsible for the facts and accuracy of the material presented. The contents do not necessarily reflect the official views of the Oregon Department of Transportation or the U.S. Department of Transportation.

The State of Oregon and the U.S. Government do not endorse products or manufacturers. Trademarks or manufacturer's names appear herein only because they are considered essential to the object of this document.

This report does not constitute a standard, specification, or regulation.

# BEHAVIOR OF FRP COMPOSITE-STRENGTHENED BEAMS UNDER STATIC AND CYCLIC LOADING

## TABLE OF CONTENTS

1.0 INTRODUCTION.....	1
2.0 METHOD.....	3
2.1 STATIC LOAD TESTING.....	3
2.2 FATIGUE TESTING.....	4
3.0 RESULTS AND DISCUSSION .....	5
3.1 LOAD TESTS.....	5
3.2 FATIGUE TESTS.....	6
4.0 CONCLUSIONS AND RECOMMENDATIONS.....	9
5.0 REFERENCES.....	11

## LIST OF TABLES

Table 2.1: Composite configurations for static load tests.....	3
Table 2.2: Composite configurations for fatigue tests.....	4
Table 3.1: Results of load tests.....	5
Table 3.2: Failure modes .....	6
Table 3.3: Fatigue test results .....	7

## LIST OF FIGURES

Figure 2.1: Test configuration.....	4
Figure 3.1: Load amplitude versus number of cycles.....	7
Figure 3.2: Load ratio versus number of cycles .....	8

## 1.0 INTRODUCTION

Externally applied fiber reinforced polymer (FRP) composites applied as a wet lay-up are increasingly being used to strengthen, repair, and rehabilitate civil structures. Performance of a structure with composites depends on the structural design and the orientation, properties, and proportion of the constituents (fibers and polymer resin). In the case of a wet lay-up, the matrix resin is also the resin that bonds the composite laminate to the structure. The resin is critical for effectively transferring strain to the composite over the life of the structure. Design engineers can choose from many composite systems with a wide range of resin properties. It is unclear, however, whether there are resin and fiber combinations that perform better than others.

A study conducted by Oregon State University and funded by Oregon Department of Transportation investigated the effects of different epoxy resin and fiber combinations on the static and cyclic behavior of small, concrete beams strengthened with FRP composites. The results of that study are reported in a masters project report from the Department of Civil, Construction, and Environmental Engineering at Oregon State University (*Seamanontaprinya, 2001*). This report is a summary of that thesis.

## 2.0 METHOD

### 2.1 STATIC LOAD TESTING

Thirty-eight unreinforced concrete beams were cast with dimensions 150 mm x 150 mm x 530 mm, using concrete with a nominal 28-day strength of 32 MPa. Twenty-four beams were reinforced with eight composite strengthening configurations using high and low modulus epoxy, high and low modulus fiber, and 1 and 2 composite layers, as shown in Table 2.1.

Table 2.1: Composite configurations for static load tests

Identification	Composite Configuration	Number of FRP Layers	Number of Specimens
CONT	Unreinforced concrete beam	0	3
1LG	Low-modulus resin with glass fiber	1	3
2LG	Low-modulus resin with glass fiber	2	3
1LC	Low-modulus resin with carbon fiber	1	3
2LC	Low-modulus resin with carbon fiber	2	3
1HG	High-modulus resin with glass fiber	1	3
2HG	High-modulus resin with glass fiber	2	3
1HC	High-modulus resin with carbon fiber	1	3
2HC	High-modulus resin with carbon fiber	2	3
			Total: 27

Mitsubishi Epotherm® L700S resin was used for the low modulus epoxy, and Tyfo® S resin was used for the high modulus epoxy. Glass fiber from the Fyfe Corporation – Tyfo® SHE-51 – was used as the low modulus fiber; and carbon fiber from the Fyfe Corporation – Tyfo®SCH-41 – was used as the high modulus fiber.

These beams, along with three unstrengthened control beams, were loaded to failure in third-point loading in accordance with ASTM C78, as shown in Figure 2.1 (*ASTM 2001*).



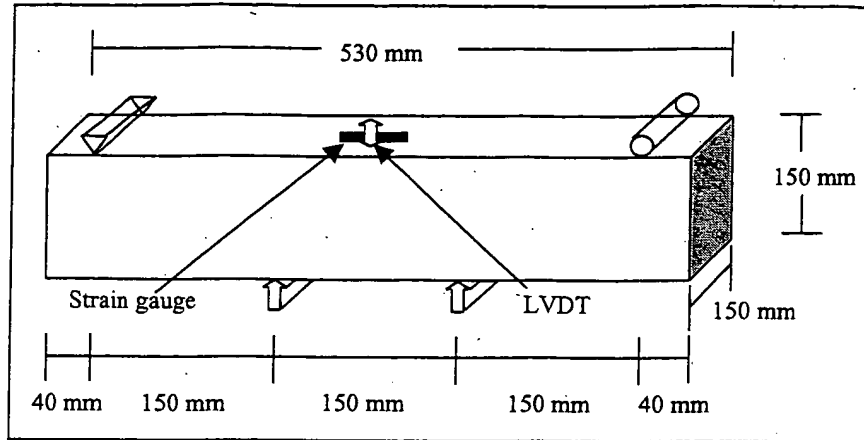


Figure 2.1: Test configuration

## 2.2 FATIGUE TESTING

The remaining 10 beams were reinforced with two composite strengthening configurations, as shown in Table 2.2.

Table 2.2: Composite configurations for fatigue tests

Identification	Composite Configuration	Number of FRP Layers	Number of Specimens
CONT	Unreinforced concrete beam	0	1
1LG	Low-modulus resin with glass fiber	1	5
2HC	High-modulus resin with carbon fiber	2	5
			Total: 11

These beams, along with one unstrengthened control beam, were fatigue tested at 0.5 Hz under the third-point loading shown in Figure 2.1. The minimum load for each test was maintained at 0.67 kN (150 lb). The 1LG configuration was the low stiffness and strength condition, while the 2HC configuration was the high stiffness and strength condition of the eight composite combinations.

### 3.0 RESULTS AND DISCUSSION

#### 3.1 LOAD TESTS

The results of the load tests are summarized in Table 3.1, and the failure modes of the tests are described in Table 3.2.

**Table 3.1: Results of load tests**

Configuration	Load (kN)	Deflection (mm)	Strain (microstrain)	Post-Crack Stiffness (kN/mm)	Failure Mode
CONT	27	0.04	230		Flexure
	29	0.05	200		
	30	NA	190		
	Mean = 29	Mean = 0.03	Mean = 210	0	
1LG	97	3.23	12500	20	Flexure with FRP rupture
	98	3.27	11900	19	
	127	4.43	15500	20	
	Mean = 107	Mean = 3.64	Mean = 13300	Mean = 20	
2LG	142	2.99	10200	36	Shear and flexure
	189	3.79	13300	41	
	195	3.78	14900	42	
	Mean = 175	Mean = 3.52	Mean = 12800	Mean = 39	
1LC	141	2.28	7800	47	Shear and flexure
	149	3.17	8600	35	
	158	3.09	9000	38	
	Mean = 149	Mean = 2.85	Mean = 8500	Mean = 40	
2LC	179	1.97	5400	74	Shear
	199	1.86	5400	88	
	210	2.48	6100	67	
	Mean = 196	Mean = 2.10	Mean = 5600	Mean = 77	
1HG	134	4.23	16400	23	Flexure with internal shear failure of laminate
	136	4.70	16300	20	
	143	5.29	17100	18	
	Mean = 138	Mean = 4.74	Mean = 16600	Mean = 20	
2HG	196	3.96	12600	42	Shear and flexure. 2 failed with concrete crushing
	203	4.69	14600	35	
	220	4.13	14600	42	
	Mean = 206	Mean = 4.26	Mean = 13900	Mean = 40	
1HC	159	3.38	9600	38	Shear and flexure. 2 had internal shear failure of laminate
	171	3.46	11600	38	
	174	3.13	9300	42	
	Mean = 168	Mean = 3.32	Mean = 10200	Mean = 39	
2HC	196	1.87	5200	83	Shear
	201	2.07	5400	76	
	223	2.17	6300	82	
	Mean = 206	Mean = 2.04	Mean = 5600	Mean = 80	

**Table 3.2: Failure modes**

Failure Mode	Description
Flexure	Flexure crack develops from tensile side in the center of specimen between loading points and propagates to compression side.
Shear	Shear crack develops on the tensile side of specimen near support and propagates about 45° angle to the loading point.
Shear and flexure	Shear crack propagates to the center of specimen, shifts to flexure, and continues to propagate to the compression side.
Internal shear failure of laminate	Shear stress in the resin exceeds its capacity
Concrete crushing	Flexural cracking with concrete crushing on compression side.

As expected, beams with 2 layers of a particular fiber type had higher load capacity and stiffness than beams with 1 layer. Also, carbon fiber produced higher capacity and stiffness in the beams than the glass fiber. The resin had no effect on the stiffness; however, the high-modulus resin increased the load capacity up to 29%. A smaller increase in load capacity – as low as 5% – was observed when the failure mode switched from a desirable flexure failure to shear failure modes in beams strengthened with the higher stiffness composite configurations. This result indicated that for properly designed beams, the resin could appreciably affect the load capacity of the beam.

### 3.2 FATIGUE TESTS

The fatigue test results are shown in Table 3.3. Load ratios were calculated using the following equation:

$$R_l = \frac{L}{L_{ult}} \quad (3-1)$$

where

$R_l$  = load ratio,

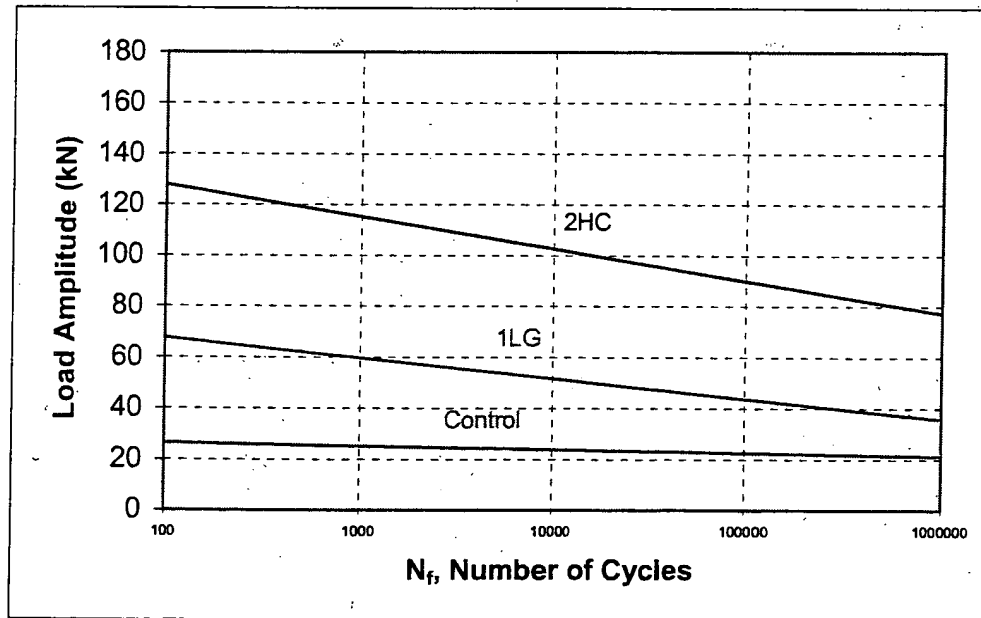
$L$  = applied load, and

$L_{ult}$  = static ultimate loading capacity

**Table 3.3: Fatigue test results**

Configuration	Load Amplitude (kN)	Load Ratio	Number of Cycles	Failure Mode
CONT	29.0	1.000	1	Flexure
	22.2	0.766	136000	
1LG	107.0	1.000	-	Flexure
	72.8	0.680	80	
	64.3	0.601	180	
	55.5	0.519	1200	
	44.6	0.417	36000	
	40.0	0.374	648000	
2HC	206.0	1.000	-	Shear and Flexure
	105.0	0.510	11700	
	104.9	0.509	13700	
	89.1	0.433	32400	
	86.4	0.419	99800	
	81.0	0.393	916400	

Figure 3.1 shows that the higher strength and stiffness composite configuration, 2HC, provided better fatigue response. Figure 3.2 indicates that the fatigue strength of the composite-strengthened beams is strongly dependent on the capacity of the beams. Equations were established to predict fatigue life for the beams used in this study.

**Figure 3.1: Load amplitude versus number of cycles**

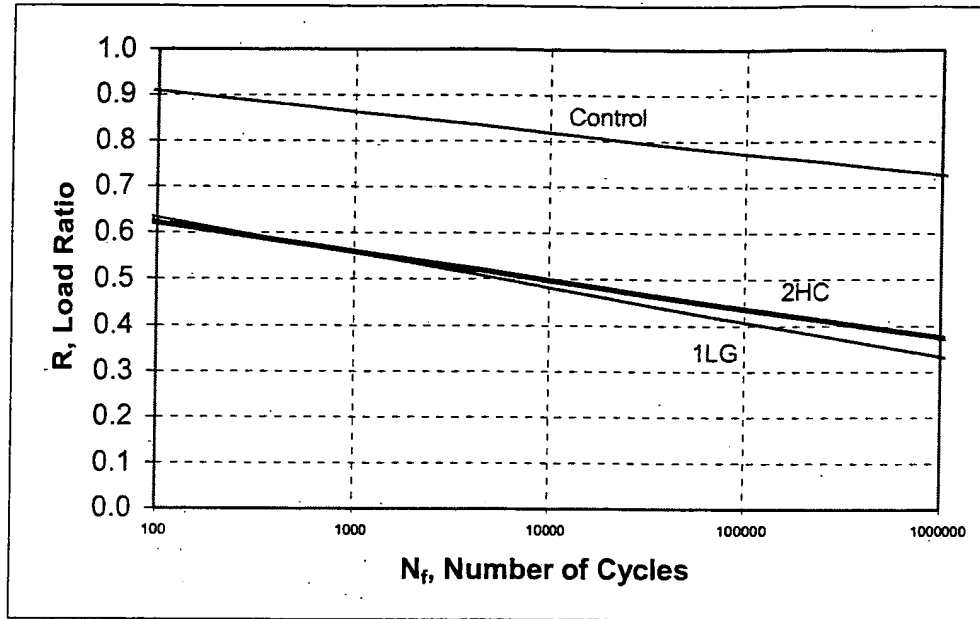


Figure 3.2: Load ratio versus number of cycles

## 4.0 CONCLUSIONS AND RECOMMENDATIONS

- Increasing the elastic modulus of the resin in a wet lay-up may increase the load capacity of FRP-strengthened, concrete beams. However, this enhancement decreases as the failure mode changes from flexural failure to less desirable failure modes.
- Because fatigue performance is dependent on load capacity, the resin effect may also increase the fatigue response of FRP-strengthened beams.
- The elastic modulus of the resin has no effect on the stiffness of beams.
- To verify and quantify the relationship between elastic modulus of the resin and performance, further testing would need to be conducted on full-size beams with realistic design configurations.

## 5.0 REFERENCES

American Society for Testing and Materials (ASTM) Subcommittee C09.61. 2001. *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. Designation ASTM C 78-00. West Conshohocken, PA.

Seamanontapriya, Dharadon. 2001 (in press). *Behavior of FRP Composite-Strengthened Beams under Static and Cyclic Loading*. Masters project report, Department of Civil, Construction, and Environmental Engineering, Oregon State University.



THE FIBERWRAP® COMPANY

## Tyfo® SEH-51 Composite using Tyfo® S Epoxy

### DESCRIPTION

The Tyfo® SEH-51 Composite is an ICBO ER-5282 listed material comprised of Tyfo® S Epoxy and Tyfo® SEH-51 reinforcing fabric. Tyfo® SEH-51 is a custom weave, uni-directional glass and aramid hybrid fabric used in the Tyfo® Fiberwrap System. The glass material is oriented in the 0° direction with aramid fibers at 90°. The Tyfo® S Epoxy is a two-component epoxy resin material for bonding applications.

### USE

Tyfo® SEH-51 Fabric is combined with Tyfo® epoxy material to add strength and ductility to bridges, buildings, and other structures.

### ADVANTAGES

- ICBO ER-5282 listed material
- Good high & low temperature properties
- Long working time
- High elongation
- Ambient cure
- 100% solvent-free
- Rolls can be cut to desired widths prior to shipping

### COVERAGE

Approximately 575 sq ft. surface area with 3 to 4 units of Tyfo® S Epoxy and 1 roll of Tyfo® SEH-51 Fabric when used with the Tyfo® Satorator.

### PACKAGING

Order Tyfo® S Epoxy in 55-gallon (208L) drums or pre-measured units in 5-gallon (19L) containers. Order Tyfo® SEH-51 Fabric in 54" x 150 lineal feet (1.4m x 45.7m) rolls. Typically ships in 12" x 12" x 64" (305mm x 305mm x 1626mm) boxes.

### EPOXY MIX RATIO

100.0 component A to 42.0 component B by volume (100 component A to 34.5 component B by weight)

### SHELF LIFE

Epoxy - two years in original, unopened and properly stored containers.  
Fabric - ten years in proper storage conditions.

### STORAGE CONDITIONS

Store at 40° to 60° F (4° to 32° C). Avoid freezing. Store rolls flat, not on ends, at temperatures below 100° F (30° C). Avoid moisture and water contamination.

### CERTIFICATE OF COMPLIANCE

- Will be supplied upon request, complete with state and federal packaging laws with copy of labels used.
- Material safety data sheets will be supplied upon request.
- Possesses 0% VOC level

002 Tyfo® SEH-51

### TYPICAL DRY FIBER PROPERTIES

Tensile Strength	470,000 psi (3.24 GPa)
Tensile Modulus	10.6 x 10 <sup>6</sup> psi (72.4 GPa)
Ultimate Elongation	4.5%
Density	0.022 lbs./in. <sup>3</sup> (2.58 g/cm <sup>3</sup> )
Weight per sq. yd.	27 oz. (913 g/m <sup>2</sup> )
Fiber Thickness	0.014 in. (0.36mm)

### COMPOSITE GROSS LAMINATE PROPERTIES

PROPERTY	ASTM METHOD	TYPICAL TEST VALUE	DESIGN VALUE*
Ultimate tensile strength in primary fiber direction, psi	D-3039	63,400 psi (575 MPa) (4.17 kN/in. width)	65,730 psi (460 MPa) (3.3 kN/in. width)
Elongation at break	D-3039	2.2%	2.2%
Tensile Modulus, psi	D-3039	1.76 x 10 <sup>6</sup> psi (20.1 GPa)	3.03 x 10 <sup>6</sup> psi (20.9 GPa)
Ultimate tensile strength 90 degrees to primary fiber, psi	D-3039	6,250 psi (43 MPa)	6,000 psi (41.4 MPa)
Laminate Thickness		0.05 in. (1.3 mm)	0.05 in. (1.3mm)

\* Design and specification values will vary based on individual project requirements and applicable safety factors. Contact Tyfo Co. LLC engineers to determine appropriate design values.

### EPOXY MATERIAL PROPERTIES

Curing Schedule 72 hours post cure at 140° F (60° C).		
PROPERTY	ASTM METHOD	TYPICAL TEST VALUE*
T <sub>g</sub> 140° F (60° C) Post Cure (24 hours)	ASTM D-4065	160° F (62° C)
Tensile Strength <sup>1</sup> , psi	ASTM D-833 Type 1	10,500 psi (72.4 MPa)
Tensile Modulus, psi	ASTM D-638 Type 1	491,000 psi (3.18 GPa)
Elongation Percent	ASTM D-638 Type 1	5.0%
Flexural Strength, psi	ASTM D-790	17,900 psi (123.4 MPa)
Flexural Modulus, psi	ASTM D-790	452,000 psi (3.12 GPa)

<sup>1</sup> Testing temperature: 70° F (21° C) Crosshead speed: 0.5 in./12minutes. Grip fixtures 2716-0315 - 20 kips  
\* Specimen values can be created upon request.



TABLE 2.1 Typical Properties of Commercial Reinforcing Fibers

Fiber	Typical diameter ( $\mu\text{m}$ ) <sup>a</sup>	Specific gravity	Tensile modulus, GPa (10 <sup>6</sup> psi)	Tensile strength, GPa (10 <sup>3</sup> psi)	Strain to failure (%)	Coefficient of thermal expansion (10 <sup>-6</sup> m/m per °C, 0-100°C) <sup>b</sup>	Poisson's ratio
Glass							
E glass	10 (round)	2.54	72.4 (10.5)	3.45 (500)	4.8	5	0.2
S glass	10 (round)	2.49	86.9 (12.6)	4.30 (625)	5.0	2.9	0.22
PAN-carbon							
T-300 <sup>c</sup>	7 (round)	1.76	228 (33.5)	3.2 (470)	1.4	-0.1 to -0.5 (longitudinal) 7-12 (radial)	~0.2
AS <sup>d</sup>	7 (round)	1.77	220 (32)	3.1 (450)	1.2	-0.5 to -1.2 (longitudinal) 7-12 (radial)	
T-40 <sup>c</sup>	6 (round)	1.81	276 (40)	5.65 (820)	2		
HMS <sup>d</sup>	7 (round)	1.85	344.5 (50)	2.34 (340)	0.58		
GY-70 <sup>e</sup>	8.4 (bilobal)	1.96	483 (70)	1.52 (220)	0.38		

Pitch-carbon							
P-55 <sup>c</sup>	10	2.0	380 (55)	1.90 (275)	0.5	-0.9 (longitudinal)	
P-100 <sup>c</sup>	10	2.15	690 (100)	2.2 (325)	0.31	-1.6 (longitudinal)	
Kevlar 49 <sup>f</sup>	11.9 (round)	1.45	131 (19)	3.62 (525)	2.8	-2 (longitudinal) +59 (radial)	0.35
Boron	140 (round)	2.7	393 (57)	3.1 (450)	0.79	5	0.2
SiC	133 (round)	3.08	400 (58)	3.44 (485)	0.84	1.5	—
Al <sub>2</sub> O <sub>3</sub>	20 (round)	3.95	379.3 (55)	1.90 (275)	0.4	8.3	

<sup>a</sup> 1  $\mu\text{m}$  = 0.000039 in.<sup>b</sup> 1 m/m per °C = 0.556 in./in. per °F.<sup>c</sup> Amoco.<sup>d</sup> Hercules Inc.<sup>e</sup> Celanese.<sup>f</sup> DuPont.

# CEMENT OR SI WAX ENT SPECIMEN

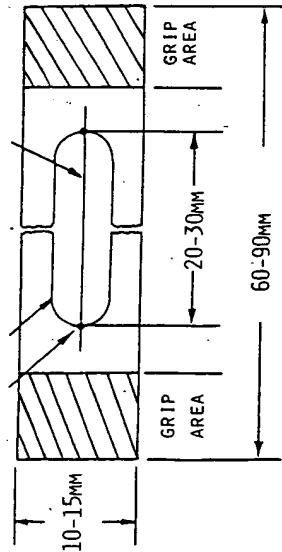


FIG. 2.2 Mounting tab for single filament testing (ASTM D3379-75).

grips of a tension testing machine, its midsection is either cut or burnt away. The tension test is carried out at a constant loading rate until the filament fractures. From the load-time record of the test, the following tensile properties are determined:

$$\text{Tensile strength } \sigma_{fu} = \frac{F_u}{A_f} \quad (2.1)$$

and

$$\text{Tensile modulus } E_f = \frac{L_f}{CA_f} \quad (2.2)$$

where:  $F_u$  = force at failure

$A_f$  = average cross-sectional area, measured by a planimeter from the photomicrographs of filament ends

$L_f$  = gage length

$C$  = true compliance, determined from the chart speed, loading rate, and the system compliance

Similar tests can also be performed to measure tensile properties of fiber strands (either dry or resin impregnated). Generally, the average tensile strength and modulus of fiber strands are lower than those measured on single filaments.

Tensile stress-strain diagrams for all reinforcing fibers in use are linear up to the point of failure, as shown in Fig. 2.3. They also exhibit very low strains to failure and a brittle failure mode. Although the absence of yielding does not reduce the load-carrying capacity of the fibers, it does make them prone to damage in handling as well as during contact with other surfaces. In continuous manufacturing operations, such as filament winding, frequent fiber breakage resulting from such damages may slow the rate of production.

The high tensile strengths of the reinforcing fibers are generally attributed to their filamentary form in which there are statistically fewer number

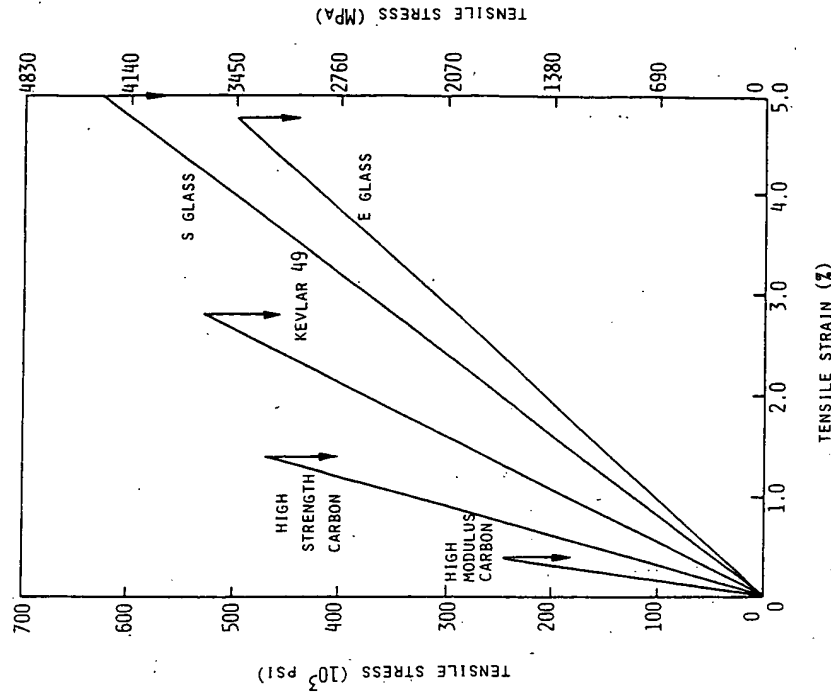


FIG. 2.3 Tensile stress-strain diagrams for various reinforcing fibers.

Table 2.4 Advantages and Disadvantages of Reinforcing Fibers

Fiber	Advantages	Disadvantages
E-glass, S-glass	High strength Low cost	Low stiffness Short fatigue life High temperature sensitivity
Aramid (Kevlar)	High tensile strength Low density	Low compressive strength High moisture absorption
Boron	High stiffness High compressive strength	High cost
Carbon (AS4, T300, C6000)	High strength High stiffness	Moderately high cost
Graphite (GY-70, pitch)	Very high stiffness	Low strength High cost
Ceramic (silicon carbide, alumina)	High stiffness High use temperature	Low strength High cost

Table 2.5 Fiber Properties

Type	Manufacturer	Tensile strength MPa (ksi)	Modulus GPa (Msi)	Density (g/cm <sup>3</sup> )
E-glass	Corning	3,450 (500)	72.5 (10.5)	2.54
S-glass	Corning	4,480 (650)	85.6 (12.4)	2.49
Carbon				
AS4	Hercules	3,730 (540)	235 (34)	1.81
T300	Union Carbide	2,760-3,450 (400-500)	228 (33)	1.76
HTS	Hercules	2,830 (410)	248 (36)	1.82
IM-6	Hercules	4,480 (650)	290 (42)	1.80
IM-7	Hercules	5,170 (750)	290 (42)	1.80
Graphite				
T-50	Union Carbide	2,070 (300)	393 (57)	1.67
GY-70	Celanese	1,725 (250)	517 (75)	1.86
Pitch, type P	Union Carbide	1,725 (250)	345 (50)	2.02
Boron	AVCO	3,280-3,660 (475-530)	365-414 (53-60)	2.1-3.0
Kevlar (aramid)	DuPont	3,800 (550)	131 (19)	1.45
Silicon carbide				
5.6 mil/C (SCS-2)	Textron	4,140 (600)	400 (58)	3.05
Nicalon	Nippon Carbon	2,070 (300)	172 (25)	2.60
Alumina				
FP-2	Dupont	1,725 (250)	380 (55)	3.70
Nexel 610	3M	1,900 (275)	370 (54)	3.75
Saphikon	Saphikon	3,100 (450)	380 (55)	3.80
Silica	—	5,800 (840)	72.5 (10.5)	2.19
Tungsten	—	4,140 (600)	414 (60)	19.3

composite and high moisture absorption. Boron fibers, not widely used at present, are useful in local stiffening applications because of their high stiffness.

Carbon (graphite) fibers come in many types with a range of stiffnesses and strengths, depending on the processing temperatures. High strength and high stiffness carbon fibers (AS4, T300, C6000), are processed at temperatures between 1200° and 1500°C (2200° and 2700°F). Ultrahigh stiffness graphite fibers (GY-70, Pitch) are processed at temperatures between 2000° and 3000°C (3600° and 5400°F). The increase in stiffness is achieved at the expense of strength, as shown in Table 2.5. Ceramic fibers such as silicon carbide and aluminum oxide have high stiffness and moderate strength and are used in metal-matrix and ceramic-matrix composites for high temperature applications.

Most fibers behave linearly to failure, as shown in Figure 2.8. Carbon fibers, such as the AS4 fiber, however, display a nonlinear stiffening effect. One important property of the fiber related to strength and stiffness is the ultimate strain or strain to failure, because it influences greatly the strength of the composite laminate.

As mentioned previously, the basis of the superior performance of composites lies in the high specific strength (strength to density ratio) and high specific stiffness (modulus to density ratio). These two properties are controlled by the fibers. A two-dimensional comparative representation of some typical fibers from the point of view of specific strength and specific modulus is shown in Figure 2.9.

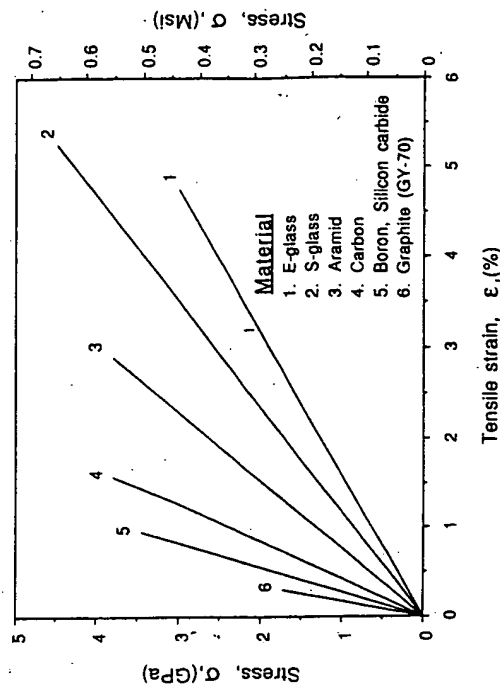


Fig. 2.8 Stress-strain curves of typical reinforcing fibers.



THE FIBRWRAP® COMPANY

## Tyfo® SEH-51 Composite using Tyfo® S Epoxy

### DESCRIPTION

The Tyfo® SEH-51 Composite is an ICBO ER-6282 listed material comprised of Tyfo® S Epoxy and Tyfo® SEH-51 reinforcing fabric. Tyfo® SEH-51 is a custom woven, uni-directional glass and aramid hybrid fabric used in the Tyfo® Formwrap System. The glass material is oriented in the 0° direction with aramid fibers at 90°. The Tyfo® S Epoxy is a two-component epoxy matrix material for bonding applications.

### USE

Tyfo® SEH-51 Fabric is combined with Tyfo® epoxy material to add strength and ductility to bridges, buildings, and other structures.

### ADVANTAGES

- ICBO ER-6282 listed material
- Good high & low temperature properties
- Long working time
- High elongation
- Ambient cure
- 100% solvent-free
- Rolls can be cut to desired width prior to shipping

### COVERAGE

Approximately 67.5 sq. ft. surface area with 2 to 4 units of Tyfo® S Epoxy and 1 roll of Tyfo® SEH-51 Fabric when used with the Tyfo® S Applicator.

### PACKAGING

Order Tyfo® S Epoxy in 55-gallon (208L) drums or pre-measured units in 5-gallon (19L) containers. Order Tyfo® SEH-51 Fabric in 54" x 150 lineal feet (1.4m x 45.7m) rolls. Typically ships in 12" x 12" x 64" (305mm x 305mm x 1626mm) boxes.

### EPOXY MIX RATIO

100.0 component A to 42.0 component B by volume (100 component A to 34.5 component B by weight)

### SHELF LIFE

Epoxy - two years in original, unopened and properly stored containers.  
Fabric - ten years in proper storage conditions.

### STORAGE CONDITIONS

Store at 40° to 90° F (4° to 32° C). Avoid freezing. Store rolls flat, not on ends, at temperatures below 100° F (30° C). Avoid moisture and water contamination.

### CERTIFICATE OF COMPLIANCE

- Will be supplied upon request, complete with state and federal packaging laws with copy of labels used.
  - Material safety data sheets will be supplied upon request.
  - Processes 6% VOC level
- ©2011 Fyfe SEH-51

### TYPICAL FIBER PROPERTIES

Tensile Strength	470,000 psi (3.24 GPa)
Tensile Modulus	18.5 x 10 <sup>6</sup> psi (12.8 GPa)
Ultimate Elongation	4.5%
Density	0.002 lbs./in. <sup>3</sup> (2.50 g/cm <sup>3</sup> )
Weight per sq. yd.	27 oz. (919 g/m <sup>2</sup> )
Fiber Thickness	0.014 in. (0.35mm)

### COMPOSITE GROSS LAMINATE PROPERTIES

PROPERTY	ASTM METHOD	TYPICAL TEST VALUE	DESIGN VALUE*
Ultimate tensile strength in primary fiber direction, psi	D-3019	63,000 psi (575 MPa) (4.17 MPa width)	63,720 psi (440 MPa) (5.3 MPa width)
Elongation at break	D-3039	2.2%	2.5%
Tensile Modulus, psi	D-3039	1.79 x 10 <sup>6</sup> psi (23.1 GPa)	3.09 x 10 <sup>6</sup> psi (23.0 GPa)
Ultimate tensile strength 90 degrees to primary fiber, psi	D-3039	6,250 psi (43 MPa)	6,000 psi (41.4 MPa)
Laminate Thickness		0.03 in. (1.3 mm)	0.03 in. (1.3 mm)

\* Design and specification values will vary based on individual project requirements and applicable safety factors. Consult Fyfe Co. LLC engineers to determine appropriate specification values.

### COMPOSITE MATERIAL PROPERTIES

Curing Schedule 72 hours post cure at 160° F (50° C).		
PROPERTY	ASTM METHOD	TYPICAL TEST VALUE*
T <sub>g</sub> 160° F (50° C) Post Cure (24 hours)	ASTM D-4068	180° F (82° C)
Tensile Strength <sup>1</sup> , psi	ASTM D-638 Type 1	10,500 psi (72.4 MPa)
Tensile Modulus, psi	ASTM D-638 Type 1	491,000 psi (3.18 GPa)
Elongation Percent	ASTM D-638 Type 1	5.0%
Flexural Strength, psi	ASTM D-790	17,000 psi (123.4 MPa)
Flexural Modulus, psi	ASTM D-790	432,000 psi (3.12 GPa)

<sup>1</sup> Testing temperature: 70° F (21° C). Crosshead speed: 0.5 in. (12.5mm)/min. Crosshairs 275-0355-00 mm.  
\* Specification values cannot be used upon request.

**This Page is Inserted by IFW Indexing and Scanning  
Operations and is not part of the Official Record**

**BEST AVAILABLE IMAGES**

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images include but are not limited to the items checked:

- ☒ **BLACK BORDERS**
- ☐ **IMAGE CUT OFF AT TOP, BOTTOM OR SIDES**
- ☐ **FADED TEXT OR DRAWING**
- ☐ **BLURRED OR ILLEGIBLE TEXT OR DRAWING**
- ☐ **SKEWED/SLANTED IMAGES**
- ☐ **COLOR OR BLACK AND WHITE PHOTOGRAPHS**
- ☐ **GRAY SCALE DOCUMENTS**
- ☐ **LINES OR MARKS ON ORIGINAL DOCUMENT**
- ☒ **REFERENCE(S) OR EXHIBIT(S) SUBMITTED ARE POOR QUALITY**
- ☐ **OTHER:** \_\_\_\_\_

**IMAGES ARE BEST AVAILABLE COPY.**

**As rescanning these documents will not correct the image problems checked, please do not report these problems to the IFW Image Problem Mailbox.**